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TO ANYONE who has worked with polymers and, in particular, fiber-reinforced plastics (FRP), orientation will be no mystery. Generally, the effect shows itself adversely in moldings but, as most of the moldings currently used are for unstressed or lightly stressed applications, the failures identified with this phenomenon are few, causing only minor annoyance to the automotive engineer concerned. In the synthetic fiber industry, orientation is of extreme importance. The fiber's high strength depends upon the manufacturer's imposed orientation of the polymer chains during processing. The orientation is controlled and the anisotropic effect is fully utilized. In molding, orientation takes place randomly in an uncontrolled and, for most cases, an unpredictable manner.

In this paper, we intend to show that this minor annoyance is a problem and is likely to be serious when FRP moldings are used for stressed automotive applications. We believe that many of the failures that occur are unsuspectingly due directly or indirectly to fiber orientation. While we cannot offer a solution to this problem, which would require an intensive study into the parameters controlling fiber orientation, we can indicate the extent of the problem and offer some ways in which it can be averted.

VARIABILITY OF MECHANICAL PROPERTIES

Our first involvement was not in the specific study of orientation but in work where we were trying to elucidate the parameters governing the wide scatter experienced in the mechanical test results from moldings of polyester glass-reinforced dough molding compound (DMC). Tensile test results varied alarmingly (6.0-63 mN/m^2). At first, we suspected the test procedure and particularly the method of specimen preparation. However, repetition of this work under carefully controlled conditions produced similar results, although the pattern of reproducibility could vary from sheet to sheet. The degree of scatter was always of the same order.

While we suspected that fiber orientation was contributing to the scatter, we did not appreciate the extent. A detailed investigation was instigated on a simple molded plaque (305 X 305 X 6 mm) of DMC (15% glass content, 6 m fiber length) to identify the principal factors involved. Eighty-seven test pieces were cut from the plaque (Fig. 1) and their cross-breaking strengths measured using a three point loading system. Strengths ranged from 31.5 to 105.6 N/mm^2. It was imme-

ABSTRACT

This paper discusses how the orientation of fiber in fiber-reinforced plastics affects automotive applications. Orientation can adversely affect moldings in applications where stress is important, especially in engine components such as front timing covers, pump flanges, oil sump bosses, and crankshaft housing. The paper examines these problems in detail and suggests ways to avert serious difficulties relating to fiber orientation.

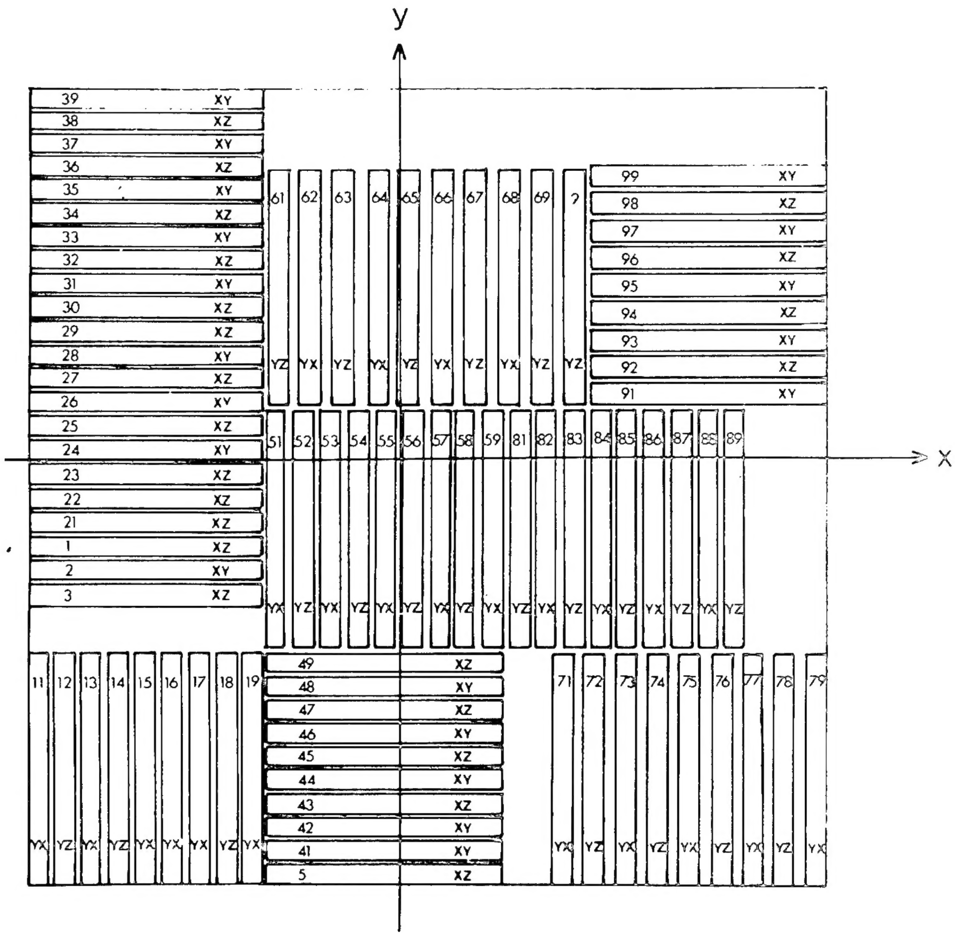

Fig. 1 - Positions and orientations of specimens

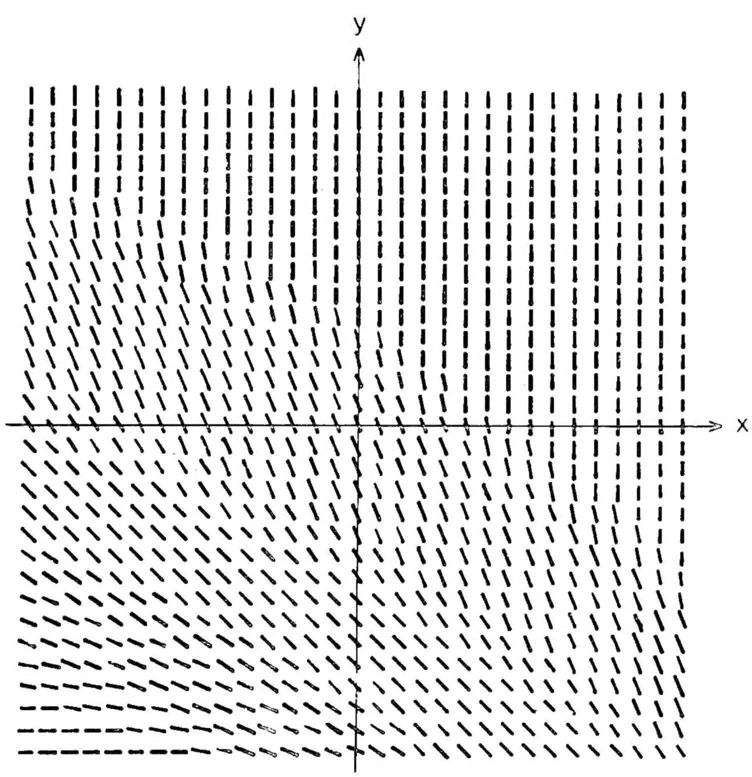

Fig. 2 - Schematic representation of preferred fiber orientation deduced from analysis of strength

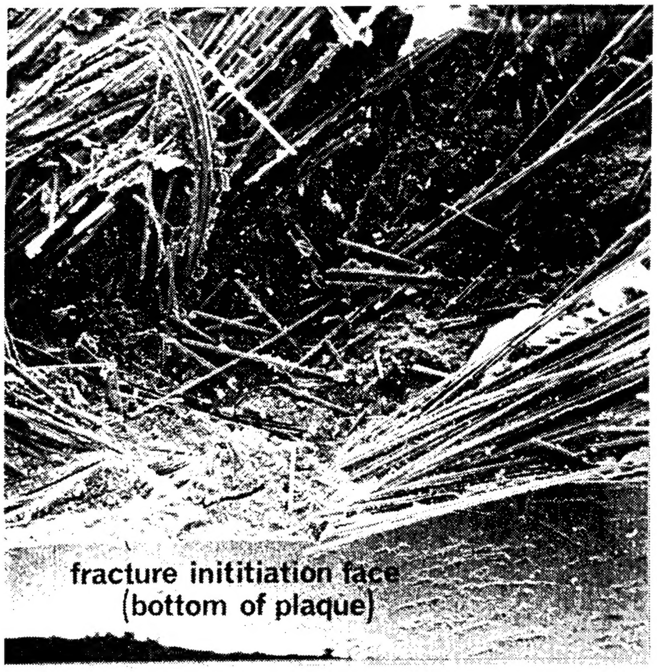

Fig. 3 - Fracture surface of low-strength specimen, stereoscan micrograph, X40 reduced 55% for reproduction

Fig. 4 - Fracture surface of high-strength specimen, stereocan micrograph, X85 reduced 55% for reproduction

diately obvious from the results that the position of the specimens had a dramatic effect on the strength. Specimens 91-99 in the upper right sector of the plaque were all weak. On the other hand, specimens with their centers near the X-axis were unusually strong. Circumferential located specimens were approximately 33 N/mm^2 stronger than those aligned radially. Mathematical analysis of the results predicted a strength of about 40 N/mm^2 for specimens with fibers oriented perpen-

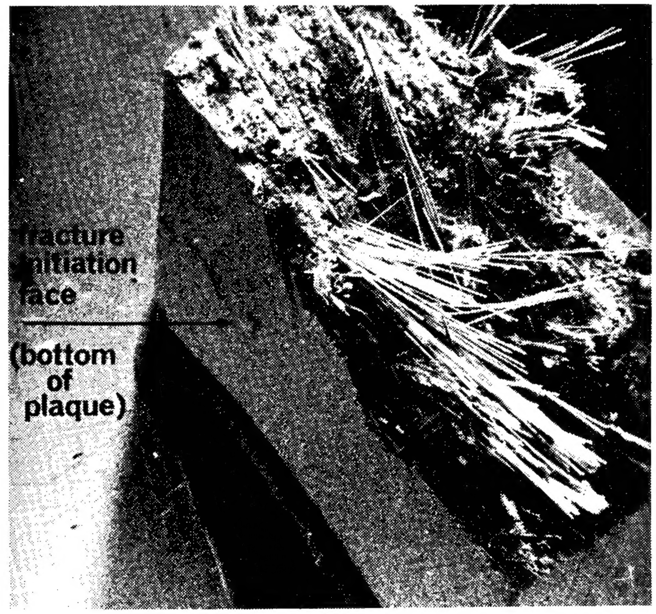

Fig. 5 - Fracture surface of medium-strength specimen, stereoscan micrograph, X15 reduced 55% for reproduction

dicularly to the axis and about 90 N/mm^2 for specimens with fibers parallel to the axis.

From microscopic examination of the fracture surface, we were able to obtain a measure of the angle the fibers made with the specimens axis and consequently with the X-axis. By correlating the angle of the fiber with the strength measured and the position of the specimen in the plaque, we were able to map (Fig. 2) the fiber pattern within the plaque and also estimate the extent to which fiber orientation was contributing to the resulting scatter—75% could be attributed to fiber orientation.

Fig. 2 shows the fiber pattern predicted from the test results. This particular pattern is unusual, in that it portrays a fiber pattern normally associated with a quarter section of a square plaque. However, the fiber pattern will only repeat itself if all the factors involved in the molding are reproduced. For instance, the fiber pattern can alter due to the positioning of the molding charge in the mold cavity or even to the cocking of the upper press platen during mold closure. Anything that produces different flow characteristics of the molding charge can create variations in the fiber orientation obtained.

This work, as previously stated, was carried out on a fairly thin molding; consequently, the orientation effects were two-dimensional. Very little tendency was observed for the fibers to orient in the third plane.

Fig. 3 is a stereoscan micrograph of the fracture surface of a low-strength specimen. It will be observed that fiber orientation lies predominantly perpendicular to the specimen's axis. A stereoscan micrograph of a high-strength specimen's fracture surface (Fig. 4) showed the fibers oriented parallel to the specimen's axis, while in Fig. 5, a medium-strength specimen depicts the fibers angularly disposed between the longitudinal and transverse axis of the specimen. Fibers so aligned will only partially contribute to the overall strength of the test piece.

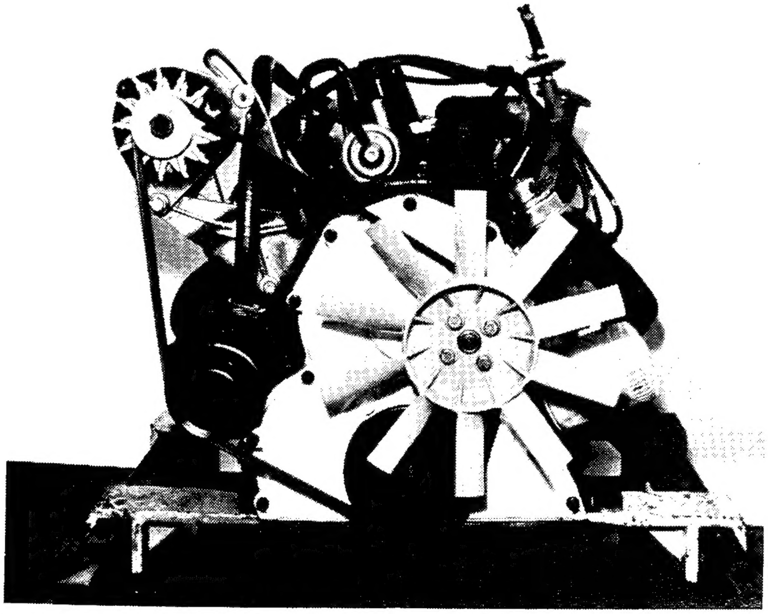

Fig. 6 - Front timing cover assembled to engine

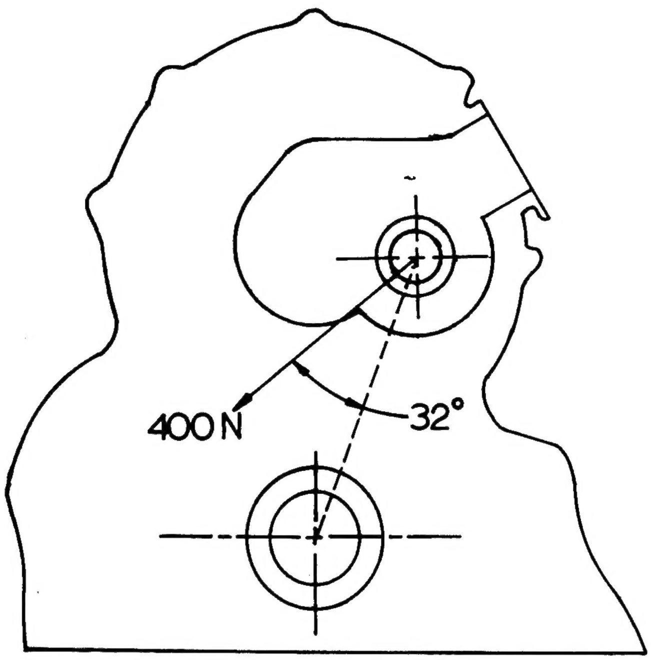

Fig. 7 - Magnitude and direction of load due to fan belt

With orientation in moldings occurring in an uncontrolled, unpredictable manner, it is not surprising that the design stress maximum for this type of material is so low (10-15% of the ultimate tensile strength). Nevertheless we have no alternative but to work with these figures if automotive industry confidence levels are to be maintained. Indirectly, we are building into components huge safety factors that are costly and do not even begin to maximize material utilization.

FIBER ORIENTATION EFFECTS ON COMPONENTS

By the examination of actual components, we intend to highlight some of the problems that arise from fiber orientation and a few ways in which they can be averted.

ENGINE FRONT TIMING COVER (Fig. 6) - The molding was made from 20% glass DMC (6 mm fiber length). The design was basically the same as its aluminum counterpart with only minor modifications such as slight thickening of the molding's outer periphery, inclusion of an extra reinforcing web at the root of the radiator fan boss, and omission of the circlip access aperture, normally included when mechanically fixing the radiator fan bearing. It is a functional component supporting the fuel pump, radiator fan, and bearing. The oil sump is bolted to the molded inserts located in bosses on the bottom sealing flange. Operationally, the component is subject to both static and dynamic stress. The fatigue stress is illustrated in Fig. 7. All tests were carried out on a 500 h engine hot test (Appendix A), inspection being made every 50 h. Tests were terminated depending upon where and to what extent cracking had occurred. Sections of the molding were cut and etched (Appendix B) to reveal the fiber orientation associated with the failure.

FUEL PUMP FLANGE - This flange was particularly vulnerable to cracking (Fig. 8). The geometry of this molding section with its retractable core and inserts created a characteristic flow in the material during molding. Etched sections (Fig. 9) showed how the material flow separated into two streams on either side of the retractable core, joining together again on either side of each of the two inserts to form a characteristic weld line. The glass fiber followed the flow, orienting itself parallel to the weld line. The glass fiber never bridged the weld line. Cracking occurred either at the resin weld line or parallel to it, following the fiber orientation on either side of the insert. Of the 36 moldings tested, only one did not fail in this manner.

Redesign and change in the molding technique is currently being undertaken to obviate failure; for example, placing molding material, SMC or DMC, into this section of the mold cavity prior to molding, thus reducing the flow of the material; or, delaying the placement of the core and the inserts until the mold is full but while the material is still in an uncured condition.

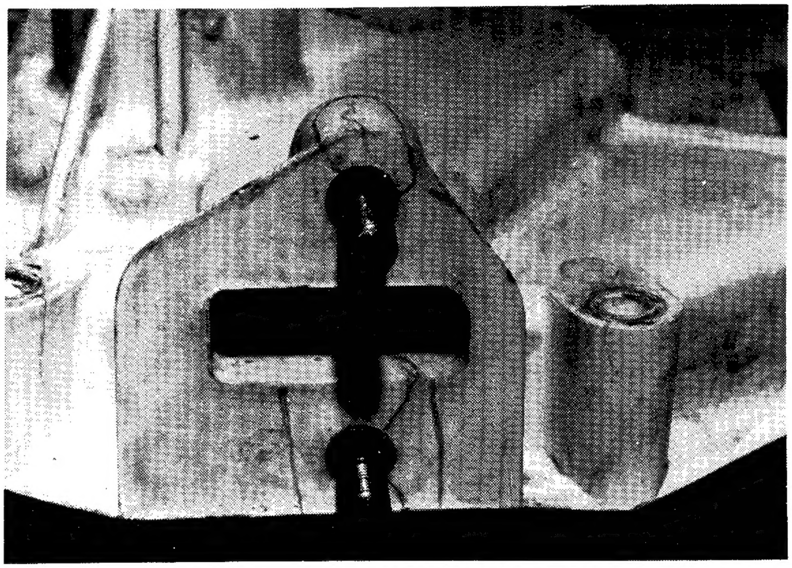

Fig. 8 - Front timing cover fuel flange showing typical cracking

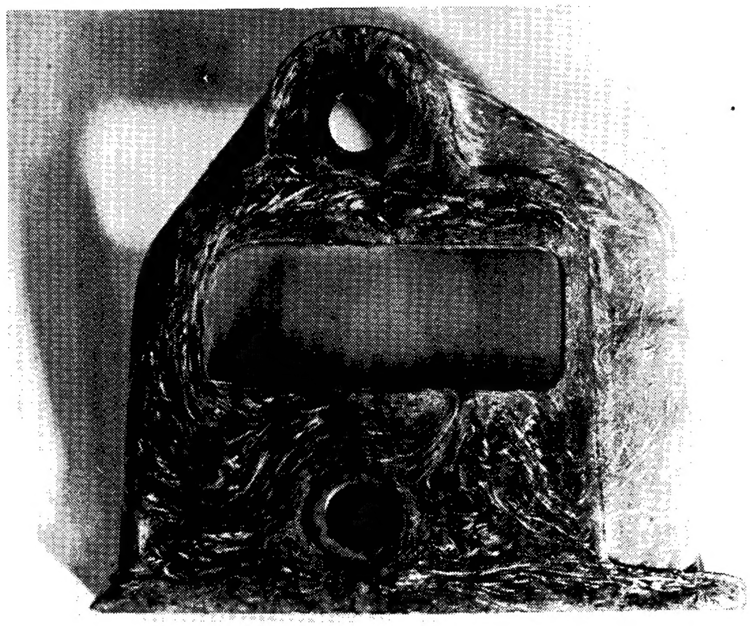

Fig. 9 - Front timing cover fuel flange etched to show fiber orientation

OIL SUMP BOSSES - Cracking of the oil sump bosses (Fig. 10) was generally present but not always in an identical position. Etched sections of the bosses (Fig. 11) showed a weld line across the top of the boss and fiber orientation parallel with the axis of the insert around the boss periphery. Cracking followed any line along the fiber orientation. No problem was experienced with the weld lines occurring on the top of the bosses because no adverse stress appeared to be present. The fiber orientation was obviously occurring due to the flow of the material around the insert. The close proximity of the insert to the molding tool wall caused the material, during flow, to be subjected to shear forces from the tool surface as well as from the inserts' surface. A combination of both of these shear forces did not allow any random fiber orientation in this comparatively thin section of molding. Delaying the placement of the insert until material flowed into the boss area and then forcing the insert into the still-uncured material could resolve this problem.

RADIATOR FAN-BEARING HOUSING - Cracking occurred in the fan-bearing housing either when pressing in the bearing or during engine test. When cracking occurred, fiber orientation was always aligned axially to the bearing (Fig. 12), which was adverse to the hoop stress operating on the fan-bearing housing.

Random fiber orientation could be achieved by lining this section of the mold cavity with SMC material. The SMC, being randomly oriented and not required to flow any distance during molding, did not produce fiber alignment.

SMC MOLDED FRONT TIMING COVER - This was the same component described above, except that SMC (25-30% glass content, 25 mm fiber length) material was used for the molding instead of DMC. The molding was generally stronger in this material. However, when this material was required to flow any distance or through relatively complex mold geometry, a similar state of fiber orientation was experienced. The longer glass fibers present, while attempting to follow the nor-

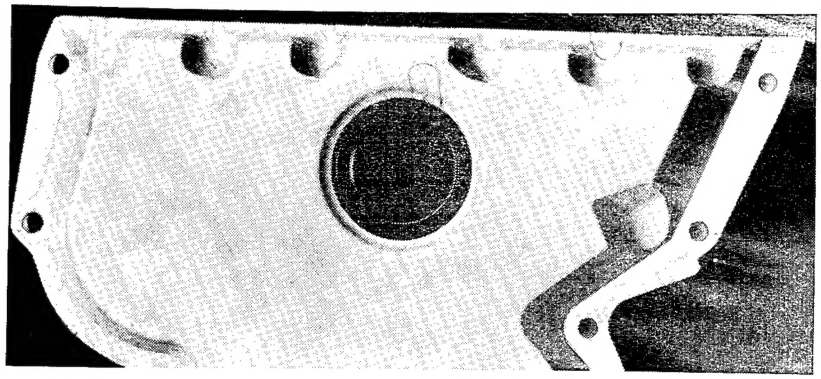

Fig. 10 - Front timing cover oil sump support bosses showing typical cracking

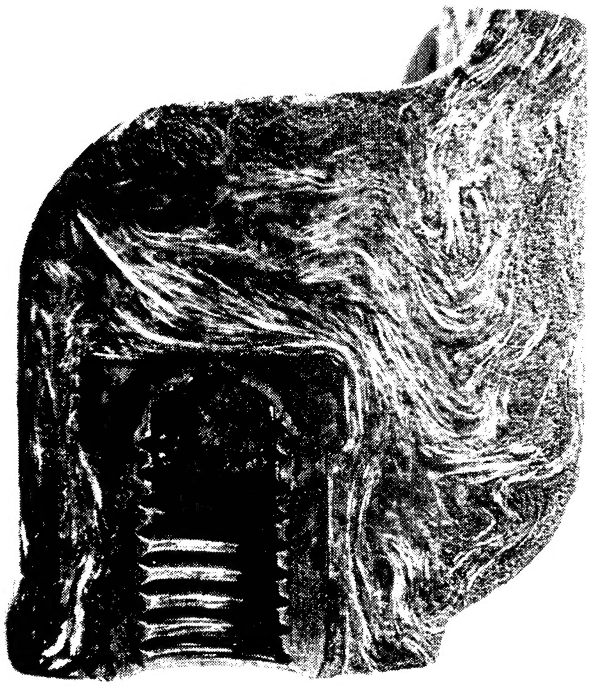

Fig. 11 - Front timing cover oil sump support boss section etched to show fiber orientation

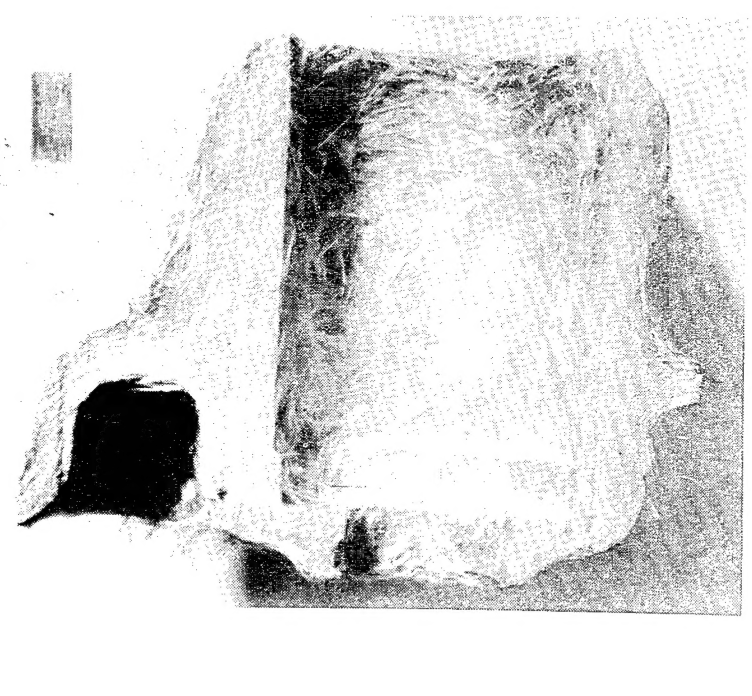

Fig. 12 - Front timing cover fan bearing housing section etched to show fiber orientation

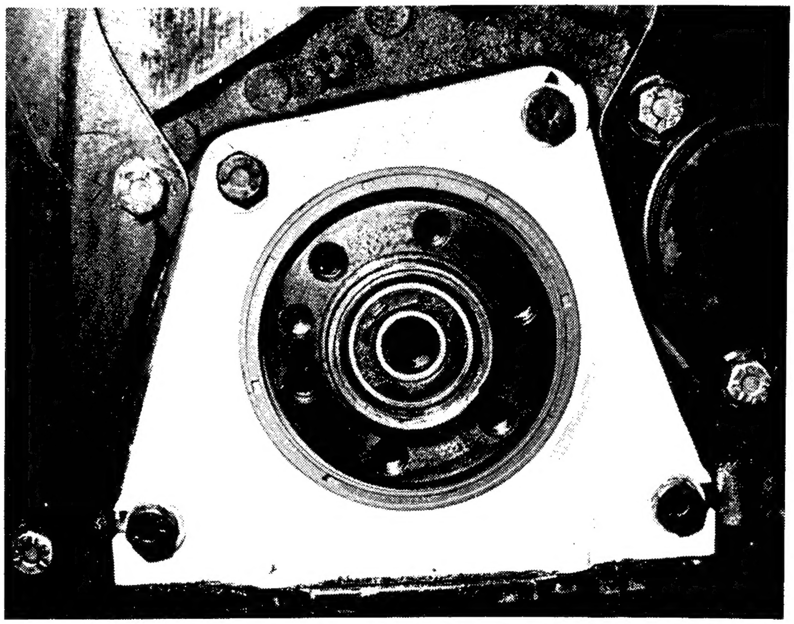

Fig. 13 - Crankshaft rear seal housing assembled to engine

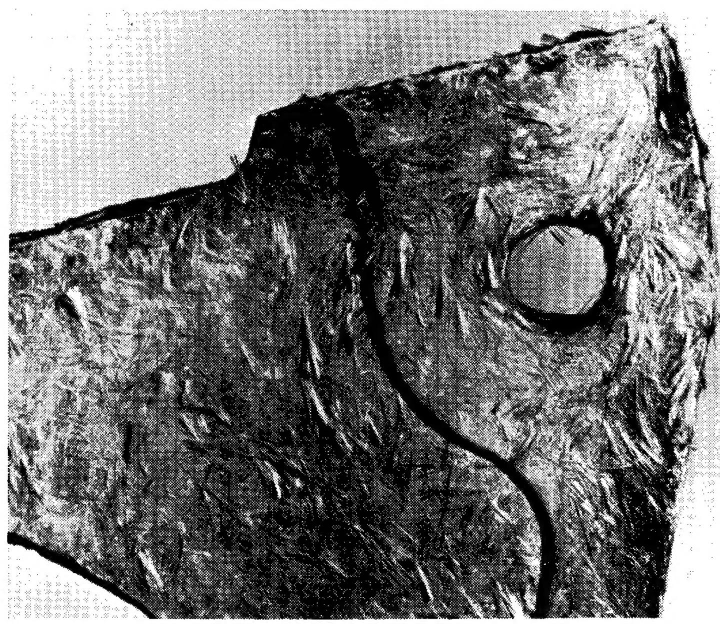

Fig. 14 - Crankshaft rear seal housing showing fiber orientation around molded-in fixing holes

mal material flow, tended to be filtered out before reaching their intended location. This created resin/filler-rich areas that were extremely weak and brittle. Unfortunately, these areas were stressed, which further aggravated the situation. Selectively loading the mold made the whole operation labor intensive and, subsequently, invoked a cost penalty.

CRANKSHAFT REAR SEAL HOUSING

The crankshaft rear seal housing (Fig. 13) supports the crankshaft rear-end rubber seal. Theoretically, the component is unstressed apart from the compressive loads produced when bolting it to the engine block. In practice, stress can also be applied due to a mismatch condition derived when assembling the oil sump pressing to the bottom of the molding.

The component was normally made from aluminum alloy, although the design, at first sight could be equally good for plastic. Low-shrink DMC (15% glass, 6 mm fiber) was chosen for this component because of the need to maintain close tolerances and flatness. The DMC moldings were first tested on engine rig tests followed by vehicle trials. No functional failures were experienced with any of the moldings tested, although cracking occurred at the bolt holes and on the bosses. Etched sections, using the technique described in Appendix B, were prepared. Again, fiber orientation associated with weld lines was present around the four fixing bolt holes (Fig. 14). Cracking followed either the resin-rich area of the weld line or the fiber orientation running parallel with it.

The molding was molded without bolt holes present, the holes being jig-bored later as a secondary operation. While this obviated the orientation problem, it also invoked a cost penalty. Closer inspection showed that this problem could be rati-

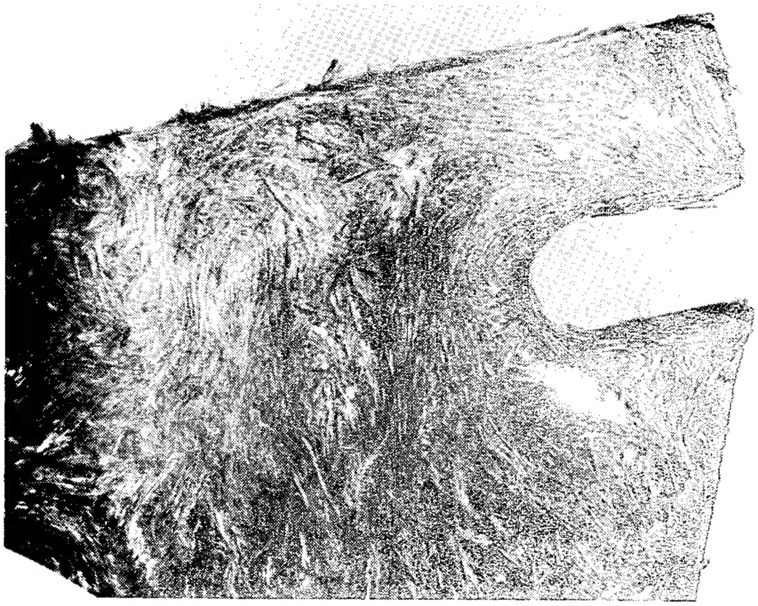

Fig. 15 - Crankshaft rear seal housing showing fiber orientation around molded-in fixing slot

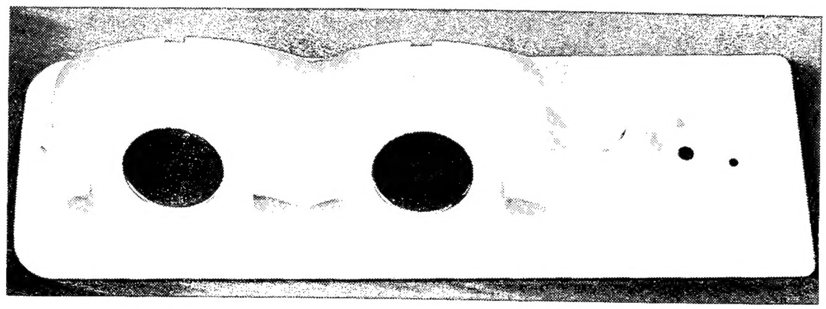

Fig. 16 - Rear tail lamp housing

fied by molding in slots instead of holes (Fig. 15). No adverse orientation was experienced with this technique, while the gasket seal face was still maintained, all at no additional component cost.

Cracking on the insert-containing boss was a similar problem to that experienced with the front engine cover. The problem was resolved by increasing the boss size, particularly the distance between the insert and the tool wall.

SURFACE CRACKING

All the cracking described so far associated with fiber orientation has occurred in depth within the molding and could lead to either immediate or eventual functional failure of the component. However, another type of cracking was also fairly common–surface cracking. This type of cracking showed itself as fine hairline cracks that penetrated the surface for a depth no greater than 0.5 mm. No further crack propagation occurred unless the component was severely overstressed in that particular area, when the crack acted as a stress raiser, as would be expected.

The surface cracks appeared on the engine moldings very early in the test period but were only apparent when the test operator wiped the white or light-colored molding with an oily rag. Oil and dirt penetrated the crack, accentuating its appearance. Only moldings completely free of cracks were put on engine test. This method proved to be the simplest way to detect cracks caused by incorrect molding procedure.

Surface cracks, as previously stated, did not impair the functionality of the component but were considered to be aesthetically unacceptable as well as involving a potentially high warranty cost when the service engineer replaced every molding containing a surface crack. Inspection of the position of the cracks indicated that they always occurred in areas with a high surface fiber orientation, the cracks following the fiber direction and induced surface stress by virtue of the component application. Change in molding procedure, while not necessarily getting rid of the fiber orientation, produced a nonadverse condition in the troublesome area. Under certain conditions of molding, it was observed that a completely random orientation at the surface could occur. Unfortunately, our work has not progressed to a stage where we could completely identify the controlling parameters.

Normally, surface fiber orientation will occur by virtue of its flow across a surface. The surface will induce a shear force in the flowing material due to friction, and fiber alignment will commence accordingly. The extent of the fiber orientation will depend upon the rheology of the material, the geometry of the mold/surface, and possibly the surface chemistry of that surface upon which the material is flowing. We believe that the material does not always flow across a mold surface but occasionally skids. This would account for the patches of ran-

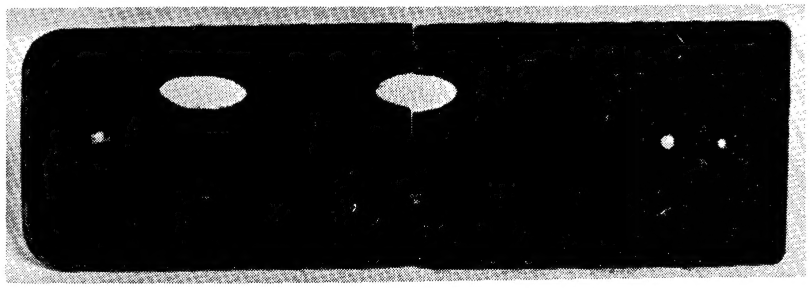

Fig. 17 - Rear tail lamp housing etched to show surface fiber orientation

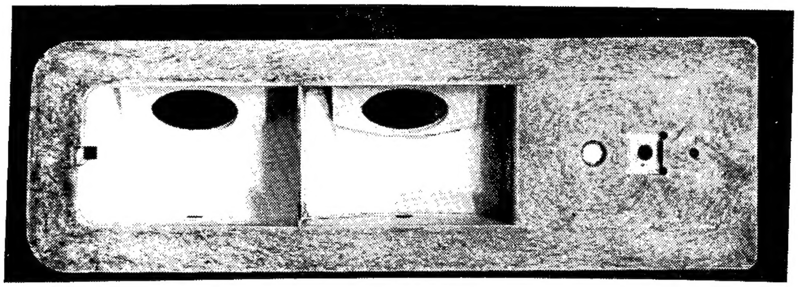

Fig. 18 - Rear tail lamp housing section showing fiber orientation in core

dom surface fiber orientation sometimes encountered in compression moldings. Injection-molding the same type of material used for the engine timing cover previously described produced a similar random surface fiber orientation. The exact parameters that produce this phenomenon have not yet been identified. The limited number of injection-molded thermoset components available restricted our appraisal of this situation, so we were not in a position to say whether this was a common occurrence or not.

Fig. 16 shows a molding of a rear lamp housing that has been injection-molded from 20% glass DMC, 6 mm fiber length. As can be seen in this molding, the sections are extremely thin; so the shear effects on the material during flow should be very high, thus producing gross fiber orientation. The etched surface of this molding (Fig. 17) shows almost complete random surface fiber orientation, apart from the slight swirl condition present around the feed sprue area. A section of this same molding with the surface skin ground off to reveal the material core shows the fiber orientation that was anticipated to occur on the surface (Fig. 18). The exact reason for this effect has not been elucidated. However, the internal forces in the flowing material must be greater than the frictional forces being experienced at the mold surface and must, therefore, become the controlling factor. Whether this is a function of the particular mold surface or the fact that the material, when injection-molded, is very close to its curing temperature and, thus, has a higher viscosity than compression-molded material, or that the material is being forced very rapidly through the mold, has not been established, but we suspect it is a combination of all these factors.

Apart from aesthetic cracking, further problems can occur as a direct result of surface fiber orientation.

MOLDED-IN FIXING HOLES

There is a reluctance on the part of the automobile manufacturer to mold-in studs as a means of fixing compression-molded components, because of the high risk of stud misplacement during molding and the consequent very costly damage that can occur to the molding tool. The tendency is to mold-in holes and use either self-tapping screws or bolts that are capable of cutting their own thread. Pull-out loads and stripping torques for the screws/bolts can be very high and provide a very good method of assembly. However, the relationship between the hole diameter and the molded skin on the inside of the molded hole, which tends to contain adverse fiber orientation, is very important. Fibers tend to align themselves parallel to the molding pin axis, and, if the pitch of the self-tapping screw or bolt is insufficient to penetrate the skin and locate the thread in the randomly oriented core material, then the pull-out load and the stripping torque will be very low indeed. The decrease is generally of a factor of four magnitude. For maximum retaining strength, fiber must lay transversely with respect to the screws/bolts axis in the areas of thread engagement (Fig. 19).

DESIGN DATA

Generation of design data also has its problems. The anisotropic effect of fiber orientation can precipitate a design engineer's nightmare. The wide variations in strength dependent upon fiber direction with respect to applied stress make it essential that the designer be aware of the anisotropy likely to be present in a molding if he is to make full use of the material's potential strength.

Orientation can be gross in that the whole of the molded section can be subject to fiber alignment or be restricted to just the surface. The depth from the surface affected by surface fiber orientation will vary from one material to another, as well as changes in the molding condition and the tool geometry. Test pieces produced by raw material manufacturers for the purpose of compiling design data will generally be subject to orientation. Unfortunately, that orientation will be only partially known and certainly unspecified. The results will be

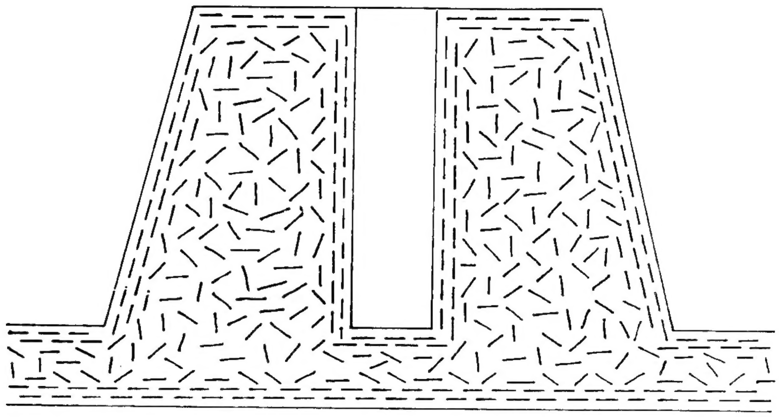

Fig. 19 - Section through boss with molded-in hole indicating fiber alignment

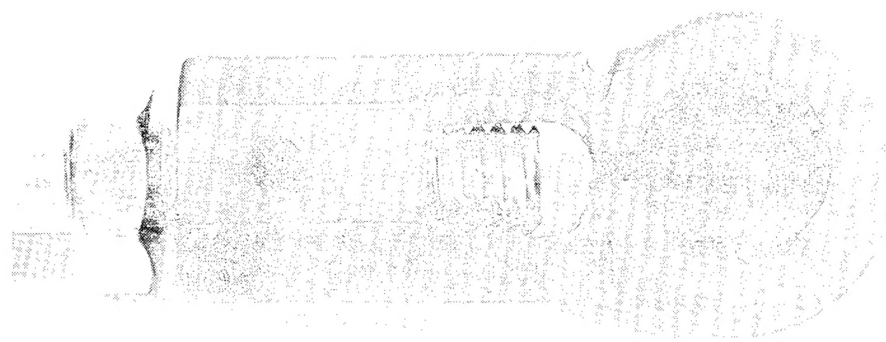

Fig. 20 - Throttle linkage

quoted as typical average mean values that will bear no resemblance to the more desirable figures for design purposes occurring in the 95% confidence bands. The figures with which the designer is expected to work leave much to be desired. They are generally not representative and certainly do not provide a true picture of the material strength likely to appear in a molding.

THERMOPLASTIC MATERIALS

All the work discussed so far is based on thermoset materials with glass reinforcement. The comments that have been made are applicable to all fiber-reinforced materials to a greater or lesser degree dependent upon the material, the length-diameter ratio of the reinforcement, bonding of the fiber to the matrix, etc. With glass-reinforced thermoplastics, the glass fiber length is very small (approximately 1 mm) when compared with the glass length used in thermoset materials. While fiber orientation is still present, it is very difficult to depict the orientation patterns by the means so far described. Etching, irrespective of the etchant used, causes the fiber to be removed due to insufficient length of fiber holding in the matrix. X-ray techniques tend to represent the three-dimensionally located fiber in a two-dimensional view, making analysis of the orientation pattern at any particular depth very difficult. Raw material manufacturers talk of fiber orientation in a material in terms of the strength the material is exhibiting in that particular test molding. The highest strength is attained from a test piece with axial orientation, but the actual percentage of alignment generally remains unknown. An assumption that is very often made is that all axially-fed injection-molded test pieces will produce axially-aligned fiber orientation. This is only true if the geometry of the feed mechanism produces a converging flow in the material. Transverse fiber orientation will be produced from the same feed location if the geometry is so arranged to produce a diverging flow. No simple method exists that portrays fiber orientation in thermoplastics as easily as those used in the study of thermosets. Consequently, it is difficult to show pictorially the problems that can occur. However, two fiber-reinforced thermoplastic components that have produced problems will be discussed.

Fig. 20 shows a throttle linkage ball socket made of unreinforced nylon. During the development of this production, a problem was experienced on vehicles fitted with automatic transmission. When high ambient temperatures were reached in the engine compartment after prolonged idle, the nylon component softened sufficiently to allow the ball connection to be pulled from the socket under throttle kickdown conditions. An easy solution to the problem was thought to be the substitution of the nylon by glass-reinforced nylon, which has a much higher heat distortion temperature. Moldings were made in the same mold used previously; unfortunately, the injection point caused the glass fiber to orient axially along the molding. Subsequent testing showed that the ball-end connection was firmly held in the socket under the most adverse temperature conditions, but the molding snapped at a point along its shank when the load was applied transversely across the fiber, producing a worse condition than previously

experienced. The higher strength and increased thermal properties of the glass-filled grade of nylon could not be utilized in this application, as the feasibility was controlled by the fiber orientation. Relocation of the feed point in the mold was difficult, and there was no guarantee that the desired fiber orientation could be attained. The problem was resolved by fixing the ball and socket with a metal clip.

Gear or sprocket wheels made from fiber-reinforced plastic are examples of other components that can fail catastrophically if insufficient design study, particularly of the feed-points, is made. Failures occur mainly in the gear teeth. If the fiber is aligned in a plane across the tooth root, then the tooth will generally not be able to withstand the bearing load applied and will fail in shear. The ideal condition within the gear tooth would be to have a completely randomly oriented fiber distribution. Surface fibers oriented to follow the tooth profile are said to have the least desirable orientation for maximum wear resistance (1)*.

Radially oriented fibers in the gears' web, if too prolific, will also cause problems of radial cracking. With gears using carbon fiber as the reinforcing medium, it has been claimed that radial orientation is desirable as the carbon fibers conduct heat away from the gear teeth to the support shaft. In this case, it is obviously necessary to compromise between possible radial cracking and good thermal conduction. Unfortunately, the control of the fiber orientation currently would have to be accomplished on a trial-and-error basis as the means of predicting fiber orientation from material rheology; tool and feed point geometry has not yet advanced to that degree of expertise.

GENERAL COMMENTS

The importance of fiber orientation cannot be overemphasized. The future use of fiber-reinforced plastics, particularly for automotive stressed applications, will depend upon maximum material utilization, the ability to achieve high confidence levels through product design, and uniform consistency of molding. As has been shown, numerous problems can occur of which the automotive engineer must be aware and able to forstall in the design and production of the component with which he is concerned. The more ambitious use of FRP will necessitate control of the fiber orientation within the molding so that the engineer can utilize the anisotropic properties rather than look on them as a curse, as is the general feeling today. The trade has attempted in the past to satisfy the engineers' requirements by trying to produce material that, when molded, adopts an isotropic nature. Plastics and, certainly, FRPs are heterogeneous by nature, and the fact that heterogeneity will show itself anisotropically when molded is something we have to accept. However, we do not have to accept that the anisotropy will always work against us. We have in our hands an effect which, if harnessed, can be utilized to our advantage. Obviously, an extensive study would have to be made to understand the parameters controlling this effect during molding, but the rewards are great and fully justifiable. The resulting component would not be designed just to satisfy the engineering requirement based upon the supposed mechanical properties of the material, but would also encompass the potential of the material achievable by the method of manufacture even if this means adding to the design geometry of the component in order to attain the desired result.

Some processes, such as filament winding, already control fiber alignment either in a polar or helical wound form. Automobile components such as leaf springs, torsion bars, and propeller shafts have been produced by this technique. Testing has shown that very high strengths can be achieved in components manufactured by this process (tensile strength > 700 mN/m^2) (2). The process is flexible and allows the strength to be concentrated where needed and gives a very significant weight saving. Helically wound glass fiber (coated with epoxy resin) exhibits a very good torsional modulus. This can be used to produce in-built flexibility into a power train while allowing greater design freedom with respect to its geometry. Simple shapes can be manufactured by compression-molding preoriented sheets of either glass or carbon fiber. For low-production specialized work, hand lay-up is always available.

Although fiber orientation is utilized in these techniques, they do not lend themselves to mass production as required by the automobile industry. There is obviously a need to study the factors controlling fiber orientation in the mass-production processing techniques before the automobile industry can fully tap the potential of these materials.

*Numbers in parentheses designate References at the end of paper.

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APPENDIX A
ENGINE TEST DETAILS

All components were engine tested in accordance with the hot-test durability procedure used by engine engineering for component validation. The components were run on an otherwise standard production Essex 3 liter V6 engine mounted on a test rig and run under no load. The engine was cycled from idle at 550-5500 rpm, 180 cycles/h, continuously for 500 h.

APPENDIX B
ETCHING TECHNIQUE

1. Immerse the sample in concentrated sulfuric acid at 150°C until fully charred and etched to sufficient depth (approximately 5 min).
2. Rinse in water.
3. Rinse in methylated spirits.
4. Dye with methyl red.
5. Allow the dyed surface to dry, dip in methylated spirits, and dry at 100°C.

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